The Effect of Visual Field Manipulations on Standing Balance Control in People with Multiple Sclerosis

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The Effect of Visual Field Manipulations on Standing Balance Control in People with Multiple Sclerosis

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Abstract

Background  
Multiple sclerosis (MS) is associated with an increased risk of falls, degeneration of sensory organization, and possible increased reliance on vision for balance control.
Research question
The aim of this study was to assess differences in standing postural control between people with MS and age and sex matched controls during medial-lateral (ML) oscillations of the visual field, with and without blinders to the lower periphery.

Methods
Ten persons with MS (mean age 54.0 ± 5.3 years) and ten age and sex matched controls (mean age: 56.3 ± 6.0 years) participated in this study. Balance control was assessed while participants stood in a Christie Cave system while wearing stereoscopic glasses that projected an immersive forest scene. Visual conditions consisted of 2 m ML visual oscillations of the scene at five frequencies (0.0, 0.3, 0.6, 0.7 and 0.8 Hz) with and without blinders to block the lower periphery.

Results and significance
The results demonstrated that, in comparison to controls, participants with MS had a significantly larger center of pressure sway in both the ML and AP direction to ML visual oscillations. Additionally, participants with MS and controls both increased center of pressure frequency content to the visual oscillation frequency, while participants with MS also increased relative power at the visual oscillation frequency in the AP direction. Blinders of lower periphery reduced the percent power at the visual oscillation frequency in both groups and reduced overall sway in participants with MS during visual oscillations. Overall, results indicate that postural balance is sensitive to visual feedback in people with MS. The elicited AP sway to ML visual oscillation could reflect errors in visual processing for the control of balance, and decreased sway in response to blocking vision of the lower peripheral field could indicate an increased reliance on visual cues to maintain balance.

Keywords
Multiple sclerosis, Virtual reality, Balance, Visual motion, Postural sway

1. Introduction & background
In this study the effect of medial-lateral oscillations of the visual field on postural sway during standing in people with MS with and without occluding lower peripheral vision was examined. In people with MS, postural instability demonstrates as an overall increase in postural sway [1,2], a delayed response to postural perturbations [3], and an increased instability when visual feedback during quiet standing is restricted or is conflicting [4,5]. These changes in postural stability likely result from the loss of afferent feedback and/or altered processing of sensory signals, including vision. In turn, impaired postural stability contributes to an increased risk of falls, which has been documented in people with MS [1,6,7]. Because of its impact on postural instability and associated risk of falls, the effects of visual feedback on postural sway in people with MS was examined in this study.

Postural control is regulated by the integration of multiple afferent sources, including visual, vestibular, and somatosensory feedback. People with MS have vestibular deficits measured by posturography [8], and somatosensory loss that impacts walking speed [9] and standing balance [10]. Coupled with decreases in somatosensation, a sensory reweighting may occur [8], such as an increased reliance on vision to compensate for the disruption to other senses, as seen in older adults [11]. Vestibular and somatosensory impairments have been associated with increased instability when vision is removed during quiet standing in people with MS, especially in the anterior-posterior (AP) direction [12]. However, people with MS have deficits in vision as well, including blurred vision, double vision, and an increased incidence of optic neuritis that could compromise vision [13]. These symptoms generally manifest in central vision loss, which can lead to an increased reliance on peripheral vision [14]. Reliance on peripheral vision may become important for motion detection, suggesting
that occlusion of peripheral vision during a whole field visual oscillation might decrease sway in people with MS. Thus, an altered utilization of lower peripheral vision in people with MS may have an important impact on postural stability; for example, lower peripheral vision is important for foot placement in walking [15], as well as properly maintaining upright orientation [16].

Manipulations of the visual field have been used to characterize how people use visual information to control standing balance. Immersive virtual reality (VR) environments in people with neurological conditions characterize the role of vision in balance and are used to develop novel therapeutic interventions. Oscillations of the visual field during standing elicit postural sway, with greater sensitivity in directions that are physically less stable [17]. When given a visual oscillation, a natural tendency to “entrain” and match the visual movement has been documented [18]. This response is proposed to be due to active swaying to minimize error between the visual perception of motion and actual motion of the body, in which larger sways could indicate increased visual reliance [11]. Entrainment to visual field oscillations, reliance on visual field, and directional interpretation of self-motion to oscillations of the visual field has not yet been investigated in people with MS.

The present study examined the effect of medial-lateral (ML) visual oscillations of different frequencies on postural sway in MS and healthy age/sex matched controls in a cave automatic virtual environment (CAVE) projection system alone and with blinders intended to occlude vision of the lower, far peripheral field. The use of ML visual oscillations provided insight into how people with MS utilize visual field information to control and regulate balance, and the importance of the lower peripheral field to interpret and appropriately respond to visual motion in MS, specifically related to ML balance control. We hypothesized that people with MS have greater reliance on the visual field for postural stability resulting in: (1) MS participants having higher sway than controls in response to visual oscillations while both groups exhibit entrainment to the visual oscillation and (2) a greater reduction in sway in MS participants compared to controls when lower peripheral vision is occluded during visual oscillations.

2. Methods

2.1. Participants

Ten individuals (6 females) with MS and ten age and sex matched controls (Table 1) participated in the study. Participants were excluded if they had pain that interfered with their ability to independently maintain balance for at least 8 min, reported orthopedic or neurological disorders, lower extremity surgeries within the last year, or uncorrected vision impairment. The study was approved by the Institutional Review Board at Marquette University, Milwaukee, WI, and all participants provided written informed consent prior to participation.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>56.3 ± 6.0</td>
<td>54.0 ± 5.3</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>78.20 ± 15.79</td>
<td>76.70 ± 23.95</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.71 ± 0.08</td>
<td>1.64 ± 0.09</td>
</tr>
<tr>
<td>BBS</td>
<td>NA</td>
<td>54.2 ± 2.9</td>
</tr>
<tr>
<td>FGA</td>
<td>NA</td>
<td>27.4 ± 3.6</td>
</tr>
<tr>
<td>ABC (%)</td>
<td>NA</td>
<td>86.4 ± 16.0</td>
</tr>
</tbody>
</table>

2.2. Experimental procedure

Prior to the experiment, MS participants completed a Functional Gait Assessment (FGA), Berg Balance Scale (BBS) and Activities-Specific Balance Confidence Scale (ABC). During the experiment, participants wore a loosely fitted fall arrest safety harness and stood on a portable force platform (BTrackS; Balance Tracking Systems Inc, San Diego, CA, USA), at a self-selected foot width, with their arms relaxed at their sides while
looking straight ahead. During the study, participants were presented with the same immersive 3D VR environment using one of two different configurations: (1) a wide-field CAVE with active stereoscopic glasses, (Christie Digital Systems Inc, Cypress, CA, USA), and (2) the CAVE with blinders placed on the glasses to block vision of the feet and lower periphery. The CAVE’s scene was projected within a 5.6 by 3.1 by 3.1 m room on three walls and the floor. The stereoscopic glasses allowed the scene to appear in 3D and provided the participant with disparity depth cues of objects in the environment. Participants performed 3 blocks of 5 conditions for each VR configuration while instructed to stare straight ahead. Each block of conditions began with an initial 20-second rest condition to acquire a “baseline” balance profile, followed by 4 randomly ordered experimental (visual oscillation) conditions in which the visual scene moved to the left and right by ±2 m for ten cycles at one of four different frequencies (0.30, 0.60, 0.70, and 0.80 Hz). These frequencies were chosen based on pilot measurements and a report that postural responses are strongest below 1 Hz [18]; multiple frequencies were used to identify possible frequency differences between group or VR modality. Between conditions a 20-second rest period was provided, (Fig. 1C), to allow a return to baseline posture before the next visual oscillation. Participants experienced each of the five conditions, four experimental frequencies and one baseline condition, 3 times per VR configuration. At the end of the experiment, participants filled out a Simulator Sickness Questionnaire (SSQ) [19].

Fig. 1. Overview of the setup. (A) The visual scene (a grassy forest and distant hills textured to resemble a realistic environment) with the direction of visual manipulations indicated. (B) Participant within the CAVE environment. The visual scene was projected onto the Christie CAVE walls. (C) An example of the visual motion signal applied medial-laterally (left/right) in the virtual environment. Four test frequencies were chosen to be below the 1 Hz limit associated with visual control of posture and were chosen at the intervals above nominal standing sway frequency. (D) An illustration of the two different VR modalities experienced by the participant(s). The grey region represents portions of the blocked visual field. The lower peripheral field of view was blocked via a black cloth that draped from the lower frames of the eyepieces all the way around the arms of the glasses to the ears. This prevented the vision of the far lower field of view (feet and ground) and the far lower periphery to the sides.
2.3. Data analysis

Data were processed with MATLAB 2017b (MathWorks, Natick, MA, USA), using custom scripts. The two-dimensional COP was calculated in the ML and AP directions using vertical forces measured from four load cells [20],

\[
COP_{ML} = 24.25 \times \frac{FR + BR - (FL + BL)}{FR + BR + FL + BL}
\]

\[
COP_{AP} = 5.5 \times \frac{FL + FR - (BL + BR)}{FR + BR + FL + BL}
\]

where FR is the front right, BR is the back right, FL is front left, BL is back left load cell, and constants were device specific values provided by the manufacturer. Each COP timeseries was passed through a zero-phase 8th order Butterworth lowpass filter (5 Hz cutoff) and segmented according to condition. Finally, the mean COP within each condition was subtracted for subsequent analysis.

Mean path length (MPL) of the COP was calculated for each oscillation and baseline condition to quantify overall COP movement. Mean path length [21] in ML and AP directions were calculated as,

\[
MPL_{ML} = \frac{1}{N} \sum_{n=1}^{N-1} |COP_{ML}(n+1) - COP_{ML}(n)|
\]

\[
MPL_{AP} = \frac{1}{N} \sum_{n=1}^{N-1} |COP_{AP}(n+1) - COP_{AP}(n)|
\]

where N is the number of data points in the condition. This measure was chosen as it best described overall postural sway. Simply using sway amplitude would disregard the variability in COP position, which is commonly associated with instability.

Spectral analysis of the COP segments was performed using the power spectral density (PSD). For all COP conditions, the PSD was calculated using the `pwelch` function with a Hamming window in Matlab. To facilitate comparisons between MS and control groups, the percent power of the PSD within a frequency window was used relative to the total power from 0–3 Hz, since MS participants typically exhibited larger total power. To characterize how well participants “tuned” COP sway in response to visual oscillations, the percent power +/- 0.1 Hz about the oscillation frequency (PPaS) was calculated and compared to the same metric during baseline (no oscillation). A change in this normalized power from baseline was used as a measure of effect of visual oscillation.

2.4. Statistical analysis

Separate three-way mixed ANOVAs were performed for MPL and PPaS (in both ML and AP direction). VR configuration (CAVE, CAVE & Blinders) and oscillation frequency (0.30, 0.60, 0.70, and 0.80 Hz) were specified as within-subject factors and Group (MS, Control) was the between-subject factor in the analyses (baseline was not an included condition as we are interested in the response to visual oscillations for these parameters). Post-hoc analyses were performed using a T-test with Tukey’s HSD correction for multiple comparisons with p < 0.05. To identify significant differences between visual oscillation and baseline conditions, repeated t-tests were used within each VR Modality and group. P-values <0.05 were denoted as statistically significant.
3. Results
The results of this study included three main findings. People with MS swayed more than controls in response to the visual oscillation. In addition, people with MS swayed in the AP direction in response to an ML visual oscillation. Finally, the addition of blinders to block vision of the lower periphery reduced PPaS in both groups, and MPL in the MS group.

3.1. Mean path length of COP
The MPL was larger in participants with MS in response to visual oscillations. As an example (Fig. 2), a representative COP trace of the MS participant had a larger sway area compared to a control and decreased sway response to the visual oscillation with the addition of blinders (i.e., CAVE & Blinders vs CAVE), which was typical across the groups. As a note, MS participants appeared to increase ML MPL from baseline as visual oscillation frequency increased, while the controls appeared to be relatively unchanged (Fig. 3A). When comparing all visual oscillation trials across frequencies and group, a between-group effect was found, in which participants with MS demonstrated a significantly greater ML MPL than controls (3 way ANOVA: p < 0.01, F<sub>1,18</sub> = 12.71) (Fig. 3C). Further, the ML MPL had a significant two-way interaction effect for Group*VR Configuration (p < 0.05, F<sub>1,18</sub> = 5.46). Post hoc analysis within the MS group between VR configuration and frequency of oscillation revealed a significant decrease in ML MPL from CAVE to CAVE & Blinders condition (p < .01, F<sub>1,9</sub> = 13.436) as illustrated in Fig. 3C. No other significant main or interaction effects were found for ML MPL.

Fig. 2. Example center-of-pressure (COP) traces of a typical MS and control participant as a function of the frequency of medial-lateral oscillation of the visual scene. The MS participant is shown in gray (left) and the control is shown in black (right) for the CAVE and CAVE & Blinders condition.
Fig. 3. Mean path length (±1 SD) for each group. MS participants are shown in gray and controls in black (A, B). The CAVE condition is in black and the CAVE & Blinders in gray (C, D). The MPL for baseline and each visual oscillation is shown for the CAVE and CAVE & Blinders for the (A) medial-lateral direction and (B) the anterior-posterior direction. The group MPL collapsed across oscillations (0.3, 0.6, 0.7, and 0.8 Hz) for each group (MS or control) and modality (CAVE & Blinders, CAVE) is shown in (C) the medial-lateral direction and (D) in the anterior-posterior direction. Asterisks denote significant differences between conditions (* p < 0.05, ** p < 0.01). Grey brackets denote between group effects while black brackets denote interaction and resulting post hoc main effects.

When presented with ML oscillation of the visual scene, MS participants swayed significantly more in the AP direction than controls (refer to Fig. 2 for visual). As an additional note, MS participants increased AP MPL from baseline with visual oscillations, while controls remained relatively unchanged (Fig. 3B). When comparing all visual oscillations across frequencies and group for AP MPL, a between-group effect was found, in which participants with MS demonstrated a significantly greater AP MPL than controls (p < .05, F1,18 = 5.19) (Fig. 3D). No other significant main or interaction effects were found for AP MPL.

3.2. Frequency response of COP

The frequency content of the COP signal changed in response to the visual oscillation in both groups. Fig. 4 shows the mean power spectrum of the COP signal across each group; a peak emerged at the driving frequency of visual oscillation for stimuli at 0.6, 0.7 and 0.8 Hz in the ML direction (Fig. 4; left column). Further, MS participants’ AP sway frequency was tuned to that of the visual oscillation. The power spectra in Fig. 4 (right column) indicated an increased AP frequency in MS participants at the visual oscillation frequency when the oscillation was 0.7 Hz.
In the CAVE condition, the PPaS increased significantly from baseline during the experimental conditions for both controls and MS participants at 0.6 Hz (p < 0.01 and p < 0.001 respectively), 0.7 Hz (p < 0.05 and p < 0.001 respectively), and for controls at 0.8 Hz (p < 0.01) (Fig. 5A,B; left). In the CAVE & Blinders conditions, the PPaS increased significantly from baseline during the experimental conditions for controls at 0.6 Hz (p < 0.05) and 0.7 Hz (p < 0.05) and for MS participants at 0.8 Hz (p < 0.01) (Fig. 5A,B; right). When comparing all visual oscillation
trials across frequencies, VR configurations, and groups for ML PPaS, no interaction effects were found for Frequency*Group or Frequency*VR Configuration. For AP PPaS, a between-subject effect was found, in which participants with MS demonstrated a significantly greater AP PPaS than controls ($p < 0.01, F_{1,18} = 13.01$) (Fig. 5C). No other interaction effects were found for AP PPaS.

Fig. 5. Percentage power of COP signal near the visual oscillation frequency (+/- 0.1 Hz) averaged across MS and control participants. Open bars denote the power during baseline and filled bars denote the power during medial-lateral oscillation of the visual scene about each of the experimental frequencies specified. For example, the percentage of power of the COP signal for the 0.3 Hz visual oscillation condition (power from 0.2-0.4 Hz) was found at baseline (open bars) and during the 0.3 Hz experimental condition (full bars), and as another example for the 0.8 Hz visual oscillation condition (range from 0.7-0.9 Hz) was found at baseline (open bars) and during the 0.8 Hz experimental condition (full bars). (A) Power of medial-lateral sway for MS participants across VR configurations. (B) Power of medial-lateral sway for controls across VR configurations. (C) Group and VR configuration across all visual oscillation frequencies for medial-lateral and anterior-posterior sway. Error bars denote ($\pm$1 SD). Asterisks denote significant differences between conditions (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).
4. Discussion

4.1. The effects of ML visual field movement on postural sway

Our results show that MS participants are particularly susceptible to oscillation of the visual scene. While both MS and control participants effectively tuned their ML COP frequency to that of the visual oscillations, MS participants significantly increased their ML COP path length. This shift in COP frequency to match the visual oscillation demonstrates a visuomotor response in both groups, and the increase in ML COP sway path length in MS suggests an additional increase in visual reliance. This is consistent with observations of increased reliance on vision in people with MS based on comparisons of sway during eyes-open and eyes-closed conditions [12].

4.2. Standing sway changes in patients with MS shown and directional sensitivity

While changes in sway pattern between people with MS and controls were expected, a novel observation in the current study was increased AP postural sway in response to ML oscillations of the visual scene in MS participants (indicated by a significantly greater AP MPL for the MS group (Fig. 3B), especially at 0.7 Hz (Fig. 4), and a significant group difference in AP PPaS in MS (Fig. 5C)). We propose two explanations for these findings: (1) a change in directional motion perception of the visual field and (2) an increased sensitivity to movement in the AP direction.

In MS there is a relationship between errors/slowness in visual processing and cognitive function [22,23]. Laatu and colleagues [24] demonstrated that slowed object recognition is associated with cognition and poor semantic task performance. In the interpretation of our results, the AP postural response to a ML visual oscillation could be indicative of slowed visual processing and/or increased cognitive load when interpreting visual oscillations, resulting in a delayed response and increased instability. This instability may manifest as movements in directions outside the ML direction. Specifically, the AP direction is less stable during standing [17], which could manifest as postural sway in the AP direction. In addition to overall slowed processing, relative differences in action potential conduction velocity of the optic nerves in people with MS might impact sway direction. Optic neuritis, which is common in people with MS [13], can induce the Pulfrich phenomenon in which medial-lateral visual motion of a pendulum is perceived to have an elliptical path. In the current study, ML oscillations of the visual scene could be perceived to have an AP component; this would explain the AP sway response to a ML visual oscillation. While the Pulfrich effect has been studied in people with MS to explain the apparent movement of viewed objects (i.e. a pendulum) [25], its effects on postural stability has not been explored.

The finding that participants with MS utilize a two-dimensional (planar) reaction in response to a one-dimensional (directional) visual oscillation might reflect an impairment in directional reweighting. Directional reweighting refers to altering the sensitivity of balance control systems in AP and ML directions. In people without neural impairments, sensitivity to balance perturbations is higher in the ML direction during ambulation (since during walking more active focus is needed on ML step placement in order to maintain stability [26]), and in the AP directions during quiet standing (due to its smaller base of support) [17]. The AP response to ML visual oscillations in people with MS could reflect hypersensitivity of the balance control system in the AP direction during standing.

4.3. Importance of lower peripheral vision during visual field movements

When exposed to conditions that obstructed lower peripheral vision, sway (MPL) was decreased only in participants with MS. Interestingly, decreases in COP movement were only documented during visual oscillation
trials; simply adding blinders during baseline standing resulted in no significant differences in sway in MS or control groups. The reduction of peripheral information may have reduced motion cues of the visual scene, which could explain the reduction in postural reactions. Horiuchi et al. found that stationary random dots to cue participants of their own sway in the peripheral visual field was important for stable quiet standing and reduced COP movement more than when in the central visual field [27]. This is supported physiologically as the peripheral field of view has a higher temporal sensitivity and larger visual angle than central vision, which is effective for movement detection [28]. Our results suggest that in people with MS, the lower peripheral field of view is used heavily for moving in response to motion.

4.4. Study limitations
The use of immersive VR can cause simulator sickness and has been documented to affect postural stability [29]. Low scores on the SSQ indicated that simulator sickness did not have a large impact on the results of this study [23]. Additionally, the BBS, FGA, and ABC were not collected for the controls as gait impairment in controls was an exclusion criterion. Normative values were assumed. Finally, it should be noted that the view blocked by the blinders may have differed slightly between participants based on height. However, the variation in height was rather small (~0.09 m) and the blinders being attached to the bottom edge of the glasses resulted in a similar blockage of body in all cases.

5. Conclusions
This study demonstrated differences in postural sway responses to ML visual field oscillations between participants with MS and controls. Specifically, people with MS reacted with a larger sway path and with increased movement in the AP direction compared to controls. Obstructing the lower peripheral visual field reduced sway in response to visual field oscillations in the MS group, suggesting an increased role of lower peripheral vision for movement perception in people with MS.

Declaration ofCompeting Interest
None.

Acknowledgment
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